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Holographic image storage in Eu^{3+}–doped alkali–aluminosilicate glasses

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Abstract

In this paper, we demonstrate that holographic information can be stored in Eu^{3+}-doped alkali-aluminosilicate glasses. The holograms were developed using a two beam mixing configuration with a write-beam wavelength (465.8 nm) corresponding to the $^7F_0 \rightarrow {}^5D_0$ transition of the Eu^{3+} ions. The images were reconstructed either with the wavelength used to record them or with wavelengths below this transition (543, 633 nm). Clear holographic images were stored using a total writing power of 5 mW and an exposure time of 20 s. In addition, clear holograms were recorded using an exposure time of 200 ms when 100 mW of the writing power was used. The exposure time and the writing power required for obtaining clear holographic images are dependent on the Eu^{3+} concentration.

OCIS codes: 160.5690, 160.2900, 160.2750, 190.7070, 210.2860, 210.4810, 90.7330

I. Introduction

Optical data storage devices are attractive due to their fast data-access time and the removability of the storage media. In particular, holographic data storage is very important because of the ability to store multiple holograms on the same spot and at different points along the thickness of the medium, which increases the total storage capacity of the media.

Many photorefractive crystals have been studied for holographic storage media [1]. The most popular of these crystals is lithium niobate ($LiNbO_3$) [2-4]. Population gratings stored in rare-earth doped crystalline solids at helium temperatures have been used in time-domain holographic memory using microsecond laser pulses [5]. Rare-earth doped glasses are hardly ever mentioned as holographic storage media. Probably this is due to the lack of extensive studies for these materials compared to the photorefractive crystals. The potential of using Eu-doped glasses in holographic information storage has been suggested by Behrens et al. [6], where the storage is suggested in terms of laser-induced gratings written in these glasses and not actual image storage. However, as we will show in this paper, Eu^{3+}-doped silicate glasses have the potential to be used as an image storage medium. In addition, Eu^{3+}-doped silicate glasses possess many of the characteristics of an ideal holographic material. These glasses are photosensitive over the wavelengths of the available lasers, specifically in the blue–green region of the spectra [7]. In these glasses, holograms can be stored at room temperature for long time periods [8-12]. Finally, Eu^{3+}-doped glasses can be mass-produced at low cost.

In this paper, we report the storage of holographic information in rare-earth doped silicate glasses at room temperature using a cw laser. We compare the holographic

images reconstructed by different wavelengths. We show how the Eu_2O_3 concentration affects the exposure time and the reconstructed image quality. Also, we demonstrate that associative holographic storage can be successfully achieved in these types of glasses. We show that relatively low power is needed to record the information in these glasses.

II. Experimental

The experimental setup used to record and read out the holograms is shown in Figure 1. A cw Ar^+ laser operating at 465.8 nm was used to record the image holograms. The recovery of the stored images was achieved by using three wavelengths, 465.8 nm, 543.7 nm, and 632.8 nm. The object beam was expanded to 1.5 cm then focused into the sample surface using a lens of 25 cm focal length. The reference beam was focused using a 50 cm focal length lens. The beam diameters at the crossing were 150 μm and 215 μm for the object and the reference beams, respectively. The angle between the two beams was 11° (measured in air). The grating thickness (the total overlap between the object and the reference beams) in this experiment was 1.3 mm. The object images were either written on microscope slides or on transparencies and placed at certain distances between the beam expander and the 25 cm focal length lens. The reconstructed images were viewed using a CCD camera connected to a laser beam profiler. These holograms were written using different laser powers, P_w, ranging from 5 to 100 mW.

Several samples with different Eu^{3+} concentrations were used to record the holograms. These samples were grown in the Oklahoma State University Crystal Growth Laboratory. The procedure used to make these samples can be found in Ref. [12]. The composition of these samples was according to the following formula: [$70SiO_2 \cdot$ $3Al_2O_3 \cdot$

$15Na_2O \cdot 12MgO]$: xEu_2O_3 all in mol.%. where x was 1.25, 2.5, 5, and 7.5. We identify these samples by the Eu_2O_3 concentration i.e., Eu1.25, Eu2.5, Eu5, and Eu7.5. Some of the linear properties for these samples are listed in Table 1.

III. Results and Discussion

In this section, we present the results of a holographic image retrieved using different read-out wavelengths. In addition, the effect of the Eu^{3+} concentration on the image quality, recording time, and recording power will be presented.

Several input images were used in the recording process. Some of the corresponding retrieved holographic images are shown in Figure 2. The images shown in this figure were recorded and retrieved using the 465.8 nm wavelength. Figure 3 shows four retrieved holographic images of the input image OSU. These holograms were read out using different wavelengths, λ_r's. Figure 3(a) shows the original image. The second image (b) was recorded using P_w=30 mW and an exposure time t_{exp}=30 s, while the read-out was done using λ_r=465.8 nm and P_r=2.5 mW. The third image (c) was recorded and reconstructed under the following conditions: P_w=30 mW, t_{exp}=30 s, λ_r=543.5 nm, and P_r=0.5 mW. The fourth image (d) was stored and retrieved using the following experimental parameters: P_w=30 mW, t_{exp}=10 s, λ_r=632.8 nm, and P_r=3.5 mW. The clarity of the reconstructed images, especially the one read with λ_w = 465.8 nm, is evidence that this material has the potential to be used as a holographic storage medium.

In these glasses, the holograms are stored for long periods of time at room temperature. The dark decay of the grating over one week is shown in Figure 4. Notice that the decay is relatively fast for the first 24 hours. However, the signal decays much

slower after that. The inset shows an Arrhenius plot for the slow dark decay. We estimate that the dark lifetime of the grating is more than 20 months. The persistent storage in this type of silicate glass is due to the mechanism responsible for production of the holographic grating [13].

The effect of Eu concentration on the image quality, writing time, and the writing power was also studied using $\lambda_w = \lambda_r =$ 465.8 nm. In general, we found that the reconstructed image had better quality as the Eu concentration increased. The exposure time t_{exp} needed for a clear image decreased as the write-beam power P_w increased. Here t_{exp} is defined as the time required to obtain 60% of the maximum diffracted power. We were able to obtain clear holographic images by using P_w=5 mW with t_{exp}=20 s and P_w=100 mW with t_{exp}=200 ms. Figure 5(a) shows the exposure time versus the write-beam power obtained for the 5 mol.% Eu_2O_3 doped sample. This figure shows that considerably low powers can be used to record information by using relatively short exposure times. In addition, at high powers, clear images can be stored for an exposure time less than 0.5 second. Figure 5(b) shows a holographic image written in the 7.5 mol.% Eu_2O_3 sample with P_w=100 mW and t_{exp}=200 ms. The fact that the writing and the erasing of these holograms occurs very fast suggests that this material, especially the samples with high content of Eu^{3+}, can be used for real time holography and dynamic holography. By using this material, we demonstrated that information could be stored using $P_w \leq$ 5 mW of total writing power. This makes these glasses attractive for a variety of holographic applications, especially as new laser sources in the blue–green region of the visible spectrum are being developed.

The sensitivity of a material can be defined as $S=\Delta n/F$ [14], where Δn is the induced change in the index of refraction and F the total fluence used in the writing process. The change in the index of refraction Δn, was determined from the experimental efficiency and the theoretical model that we have previously developed [15]. For example, the sensitivity of Eu5 is $S=1\times10^{-8}$ cm^2/J which is three orders of magnitude smaller than the values reported for $LiNbO_3$ [16] and hydrogen treated germano-silicate glass [14].

The elementary dynamic range of Eu5 glass is shown in Figure 6, which shows the change in the index of refraction Δn (as described above) versus the signal power. These data were obtained using the same procedure reported in Ref. [17]. The experimental setup is similar to the one shown in Ref. [12]. The write beams power ratio was varied by changing the power of one of the write beams. Our data show that the dynamic range of Eu-doped silicate glasses is not as large as that of photorefractive crystals [18]. However, this is expected since our Δn value saturates at $\sim10^{-4}$ yielding value of S considerably lower than those of photorefractive materials, as previously discussed.

Figure 7 displays four reconstructed images written in Eu1.25, Eu2.5, Eu5, and Eu7.5 samples using P_w=50 mW, P_r=2.5 mW, λ_r=465.8 nm, and different exposure. In the case of image (c), the diffracted intensity was small due to the short exposure time used to record this image. These results clearly demonstrate how the Eu concentration affects the exposure time needed to write a hologram.

We were able to demonstrate an associative holographic memory. This was achieved by putting a double slit in the path of the reference beam, while the OSU input

image was positioned in the path of the object beam. The slit width and the slit separation were both equal to 1mm. After the recording process was completed, the double slit and the OSU input image were removed, and the images shown in Figure 8 were obtained. The OSU image was reconstructed when the reference beam was used to read the holographic recording, while image (b) was obtained when the object beam was used to read the hologram. It is worth mentioning that image (b) should appear as a dark line surrounded by light from all directions. This is what we saw when this image was projected on the surface of a white card (a dark line in the center of the diffracted beam). The poor resolution and clarity of the features are due to the CCD camera that has been used. This demonstrates clearly that a faithful associative recording can be done using Eu-doped silicate glass.

These results show clearly that holographic images stored in Eu doped silicate glasses can be reconstructed using wavelengths other than the wavelength that was used to record them. This is important because it gives flexibility as to the wavelength that can be used to read out the stored information. Also, it solves the problem of hologram degradation during the read-out process when using the same wavelength that was used to store the hologram. For example, the hologram of the first image disappeared after a few seconds of continuous reading using $\lambda_w = 465.8$ nm. The results showed that the image quality is not as good when reconstructed using $\lambda_r \neq \lambda_w$. In addition, it is not easy to retrieve all the stored information using $\lambda_r \neq \lambda_w$ without knowing the experimental geometry that was used to record the hologram [19]. This is probably one of the reasons that led researchers to look for ways of recording holograms so that when they are retrieved using the same wavelength that was used to record them, no total or partial

erasing occurred. Researchers dealing with photorefractive crystals have used several techniques to fix the holographic grating so that one can write and read the information without appreciable loss of the recorded hologram [20, 21]. Examples of these methods are thermal fixing and two-photon absorption.

In Eu-doped silicate glasses, the hologram degradation is also a problem when the recording and the reading of the holograms are done using 465.8 nm. These samples have the maximum photosensitivity at this wavelength due to the absorption of light by the Eu^{3+} ions. However, we recently showed that strong holographic gratings can be written in Eu doped silicate glasses using several wavelengths in the blue-green region of the spectrum including 488 nm [7]. The attractive feature of the 488 nm wavelength is that Eu doped silicate glass is not strongly sensitive to this wavelength. This means that relatively high power is required during the writing process to achieve efficient grating. However, when reading the hologram, very low power is needed (~1 mW), which does not produce any appreciable erasure to the stored information. In addition, the 488 nm line of the argon-ion laser can give more than 2 Watts of power.

IV. Conclusion

We demonstrated that holographic images could be stored for long periods of time (over 20 months) in Eu-doped alkali aluminosilicate glasses at room temperature. These holograms can be stored using laser power as low as 5 mW. We demonstrated that clear holograms could be written in 200 ms exposure time when 100 mW of write beam power was used. In addition, as the Eu_2O_3 concentration increased, the time and the power needed to form a clear hologram decreased.

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Figure captions

Fig. 1. Experimental setup used in obtaining the data. M-mirror, BS-beam splitter, BE-beam expander.

Fig. 2. Holographic images stored in the Eu5 sample (a) happy face, (b) airplane, (c) ARO (Army Research Office), (d) chess piece, (e) horizontal lines, and (f) thumbs up.

Fig. 3. (a) The original image. (b), (c), and (d) are the reconstructed images using λ_r=465.8 nm, λ_r=543.5 nm and λ_r=632.8 nm, respectively. All images were recorded using λ_w =465.8 nm. See text for the rest of the parameters.

Fig. 4. The dark decay of the persistent grating. The inset is a semi-log plot of the normalized diffracted power as a function of time for the slow decay. The solid line is least-square fit to the data.

Fig. 5. (a) Exposure time versus write-beam power using Eu5. (b) Reconstructed image recorded in Eu7.5 with t_{exp}=200 ms, P_w=100 mW, and λ_w=λ_r= 465.8 nm.

Fig. 6. A log-log plot shows the induced change in the index of refraction as a function of the writing beam power ratio. The solid line is a guide to the eye.

Fig. 7. Reconstructed images stored in (a) Eu1.25 sample with t_{exp}=120 sec (b) Eu2.5 Sample with t_{exp}=10 s (c) Eu5 sample with t_{exp}=2 s (d) Eu7.5 sample with t_{exp}=1 s. All images were recorded and reconstructed using P_w=50 mW, P_r=2.5 mW, and λ_r=465.8 nm.

Fig. 8. Results of the associative recording holograms. (a) The OSU image as read by the reference beam. (b) The slit image as read by the object beam.

Table 1. Some of the linear parameters for the samples used in this study. L is the sample thickness, $n_{465.8}$ is the index of refraction at 465.8 nm, and $\alpha_{465.8}$ is the absorption coefficient at 465.8 nm.

Sample	**L(mm)**	$n_{465.8}$	$\alpha_{465.8}$ **(cm^{-1})**
Eu1.25	3.92	1.504	1.050
Eu2.5	2.20	1.523	1.419
Eu5	4.52	1.570	2.665
Eu7.5	2.02	1.600	4.471

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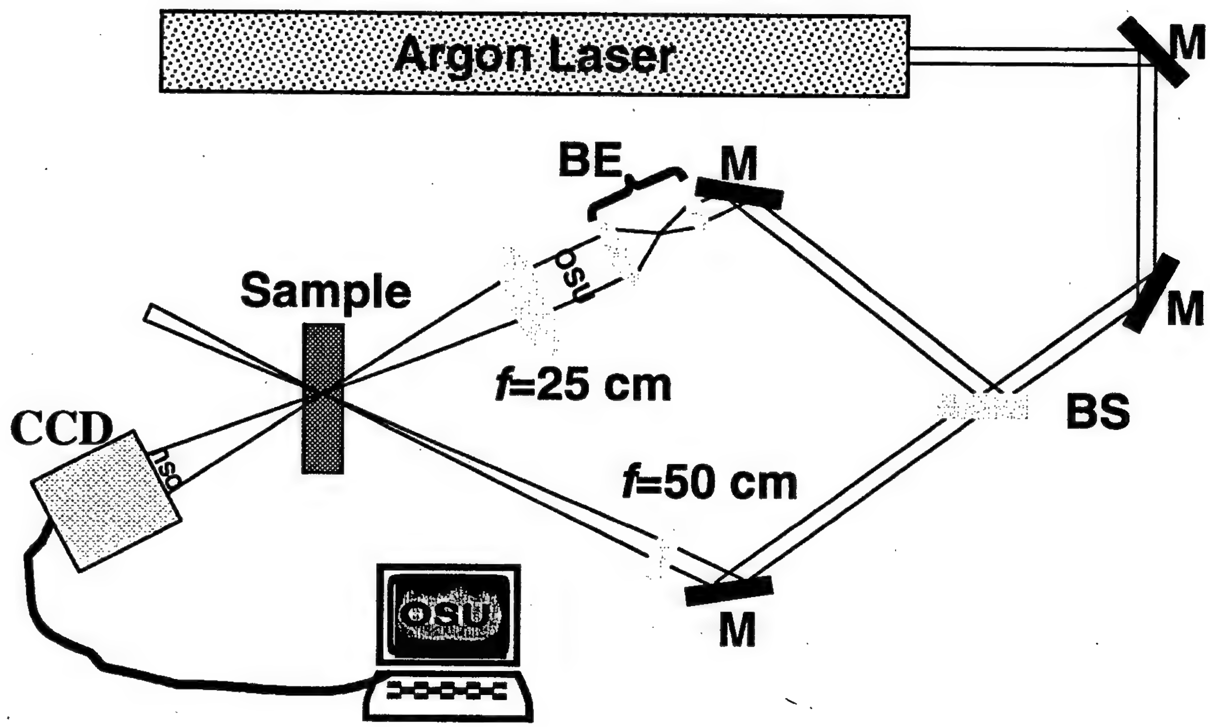

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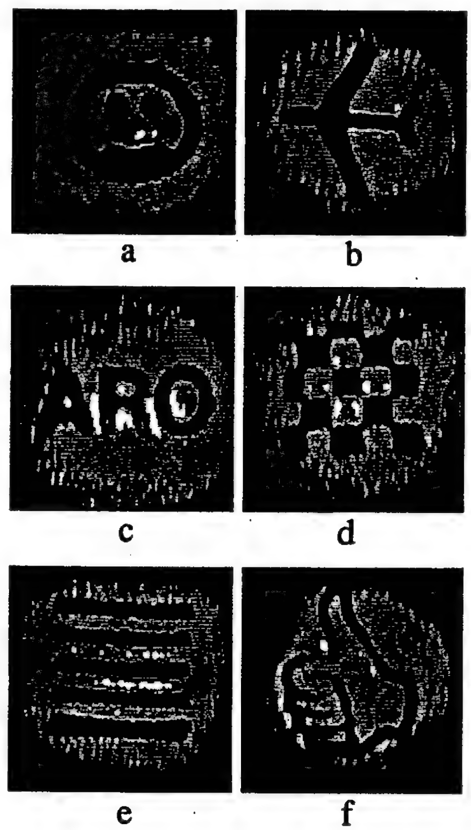

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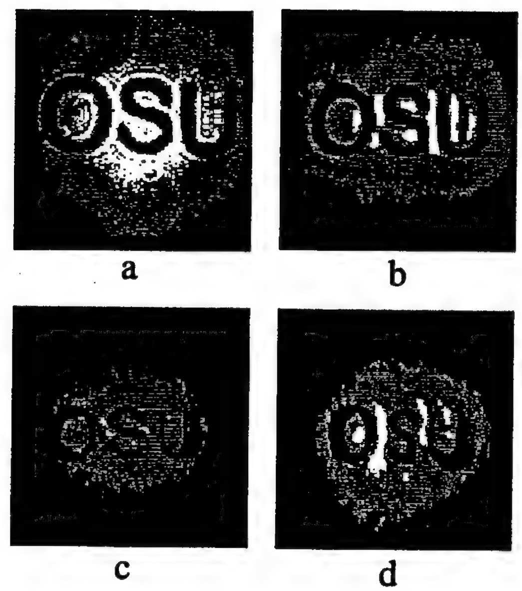

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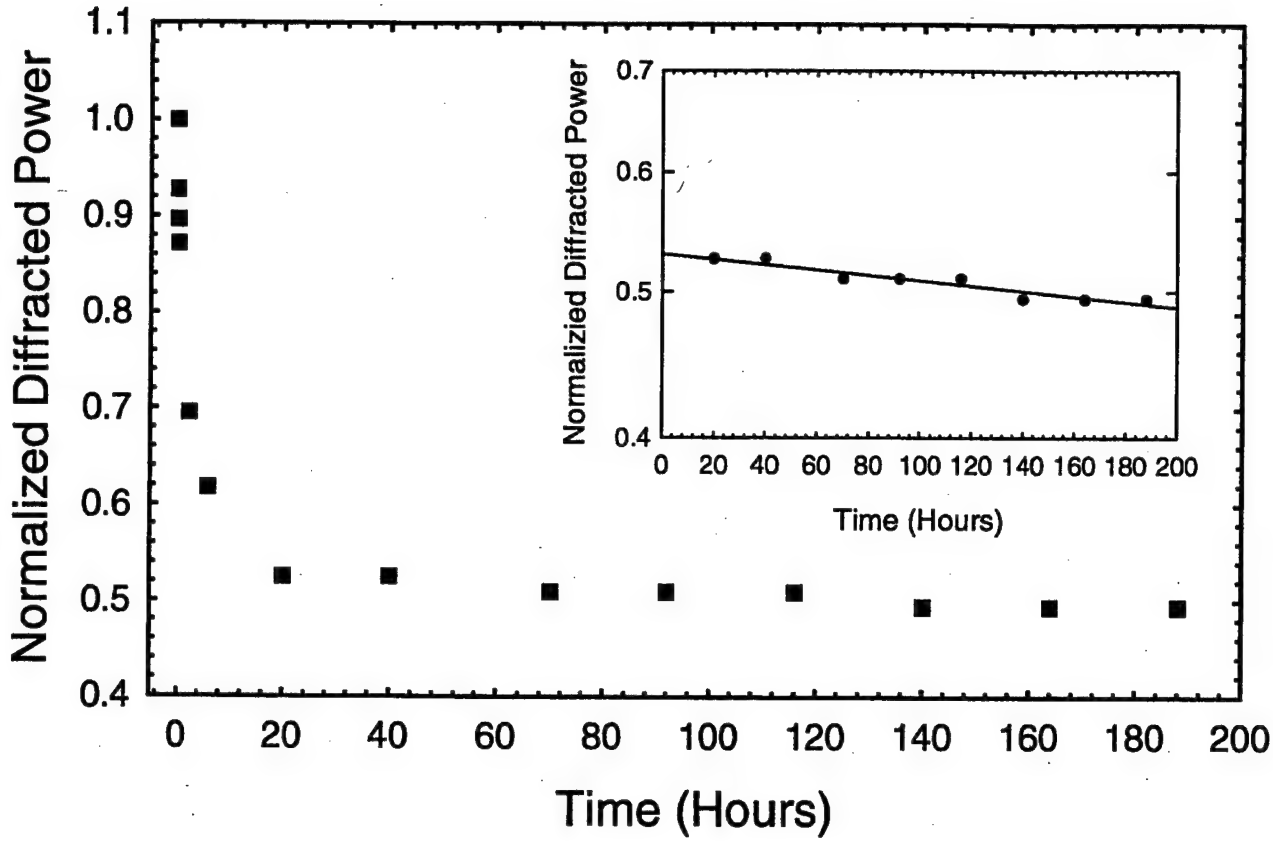

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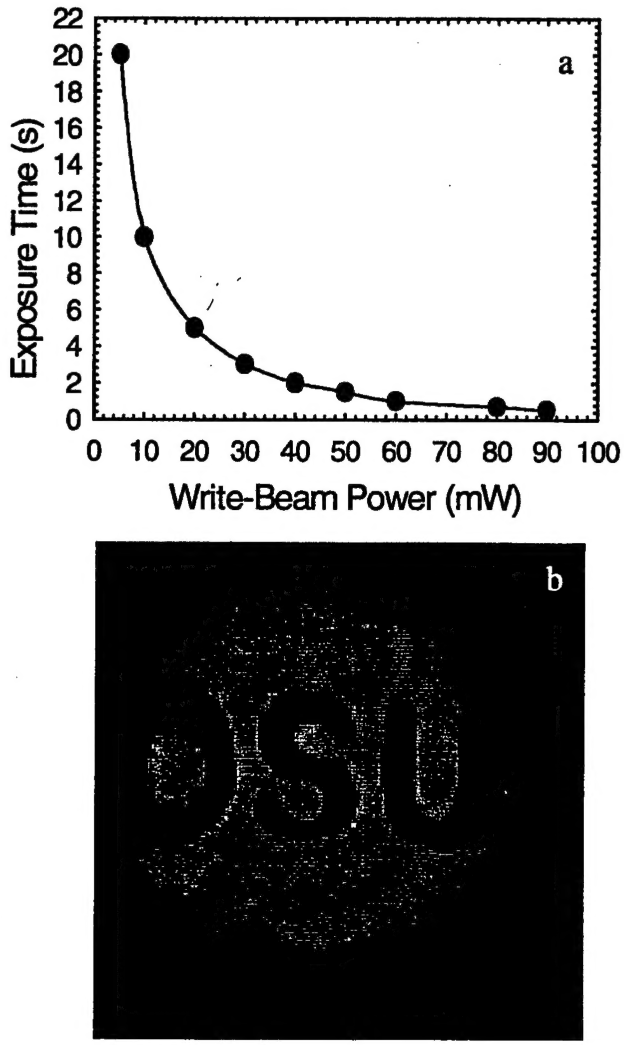

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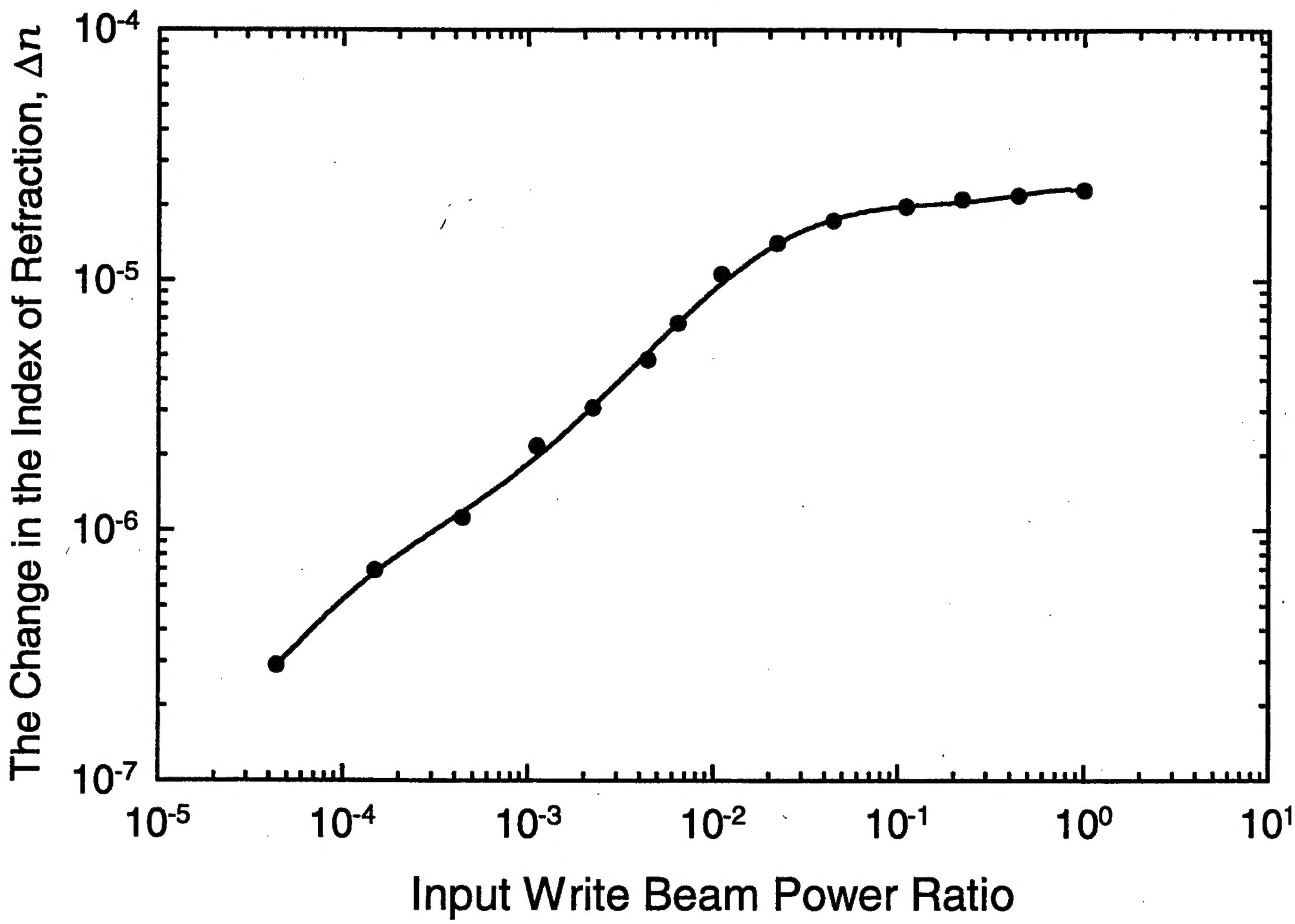

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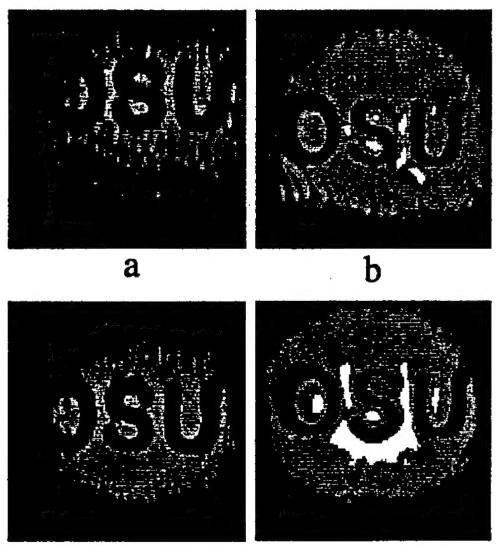

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